The Southern Oscillation, Ocean-Atmosphere Interaction and El Nino

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INTRODUCTION

The ocean and the atmosphere are not two separate fluids but rather, form the two most important components of a large heat engine that determines the fluctuations of our climate. Large-scale, ocean-atmosphere interaction has been put firmly into the forefront of research by the work of Bjerknes and Namias and through the activities of the North Pacific Experiment (NORPAX). One of the largest signals in the ocean-atmosphere system on time scales of a few years is the Southern Oscillation, and related to it are the El Nino events along the coast of South America. Today I will address the question: Why does the ocean-atmosphere system oscillate? I really should not even use the term "oscillate," because an oscillation is understood as a regular phenomenon, like the tides; in climate we rather have to deal with "vacillations." It might also be useful to emphasize that the ocean-atmosphere system is a fluid system and that one of the main properties of such a system is turbulence, on all space and time scales.

The Southern Oscillation

The Southern Oscillation constitutes an exchange of mass between the eastern and the western hemisphere in the tropics and subtropics, as is so very well illustrated in the original analysis by Berlage (Figure 1).

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There are four major atmospheric systems on the surface of the globe. At this point it might be useful to look at their relations and their properties:

1. The Antarctic westerlies, a permanent feature of the global circulation, changes somewhat seasonally, but we know little so far about its interannual variability, which is probably large.
2. The Easter Island High, the biggest of the southern hemisphere subtropical high-pressure systems, situated over the biggest ocean, is subject to moderate seasonal and large interannual fluctuations.
3. The Indonesian Low, situated over the largest warm water area in the world, is subject to large seasonal north-south migrations.
4. The Asian High, the biggest high-pressure system developed in winter over the biggest continent, is a strictly seasonal phenomenon.

While atmospheric circulation over the northern hemisphere is largely ruled by seasonal events and their variations from year to year, over the southern hemisphere interannual variations are more important. The Southern Oscillation links these two different regimes and is consequently an expression of global atmospheric variability. It does not fluctuate with a simple periodicity, and this is probably its most important characteristic. There are periods of high intensity and periods of low intensity, but rarely is the hypothetical mean state established (Figure 2). Seasonal and interannual variations are of about the same amplitude.

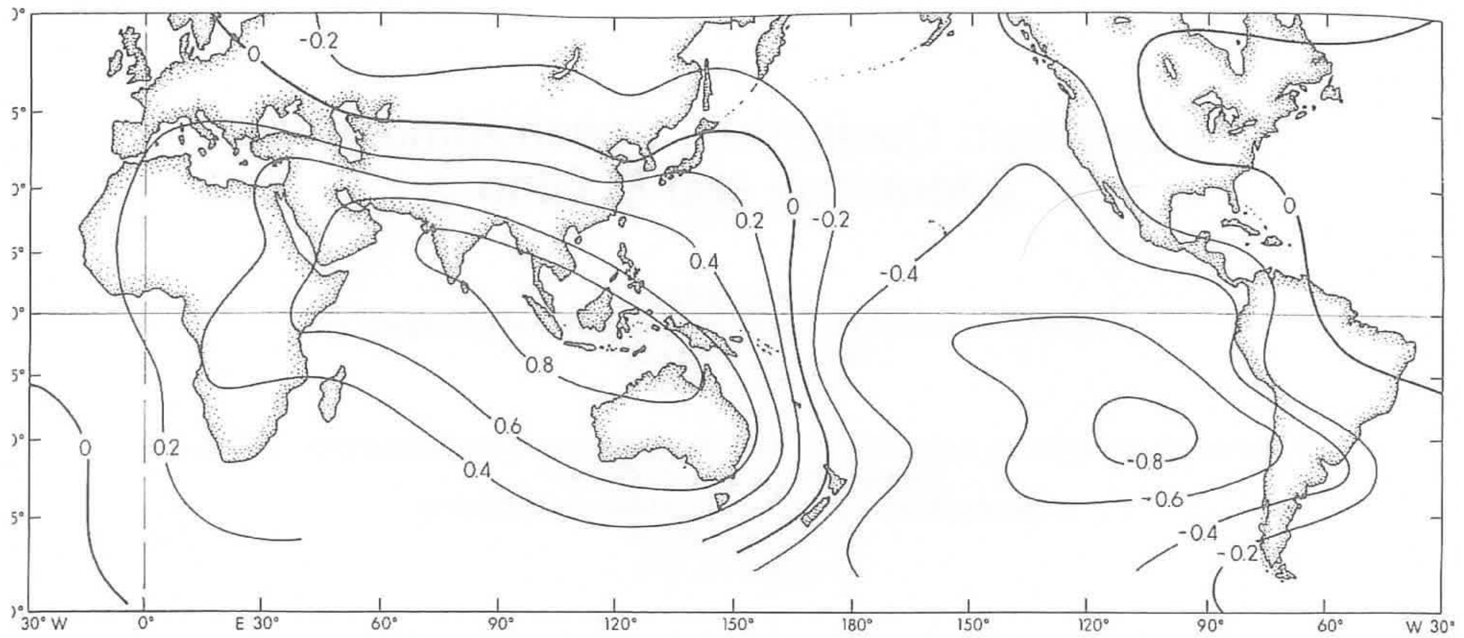

Figure 1. The southern oscillation. Correlation of annual mean atmospheric pressure with Jakarta (after Berlage).

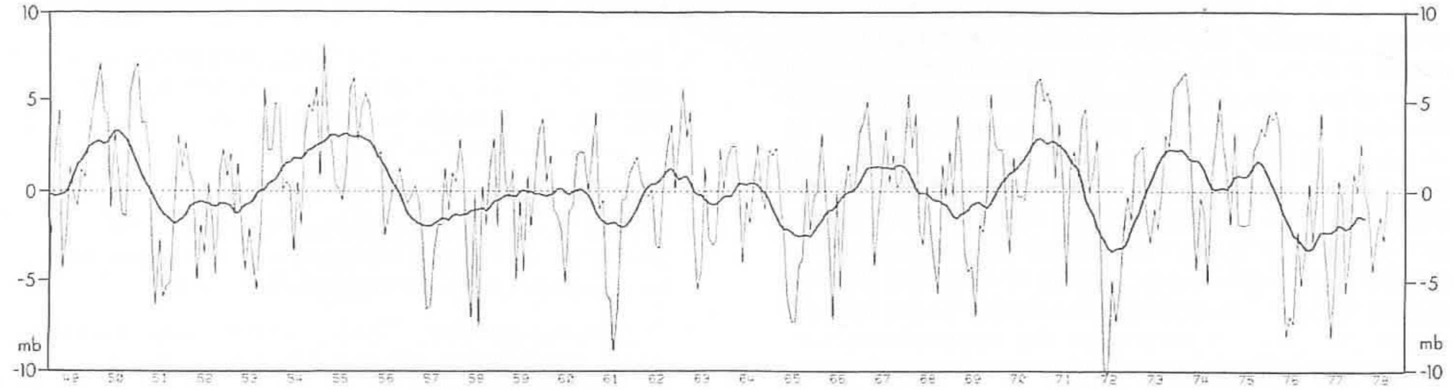

Figure 2. The Southern Oscillation as given by the difference of atmospheric pressure between Easter Island and Darwin, Australia from 1949 to 1978 relative to a mean of 10.3 millibars. The thin line gives monthly means, the heavy line the 12-month running mean.

The main question is probably: Why does the Southern Oscillation fluctuate? One could seek the answer entirely within the atmosphere, and then the ocean response would be entirely passive. But Bjerknes has demonstrated that the ocean is intimately involved, so we should first explore the relationship between oceanic and atmospheric events. There are apparently two stable states, each lasting for periods of more than a year, when they occur. The Walker circulation (Figure 3) takes place in the vertical plane along the equator. The trade winds blowing westward carry progressively moister air. Where this warm, moist air ascends it causes heavy rainfall. At higher levels the dryer air returns eastward where it is subject to sinking motion, closing the cycle. The Walker circulation is intimately linked to the Southern Oscillation, to the development of the southeast trades, and to the variations of sea surface temperature along the equator.

The Two Stable States

It is worthwhile to consider first the conditions during the two stable states. During the high-intensity state the Easter Island High pressure system is strong, the Indonesian Low is intense, and the pressure gradient between the two is strong. This situation results in strong southeast trade winds, strong equatorial upwelling, and a strong South Equatorial Current. The result is an accumulation of warm water in the western Pacific Ocean, a depression of the thermocline and an increase of sea

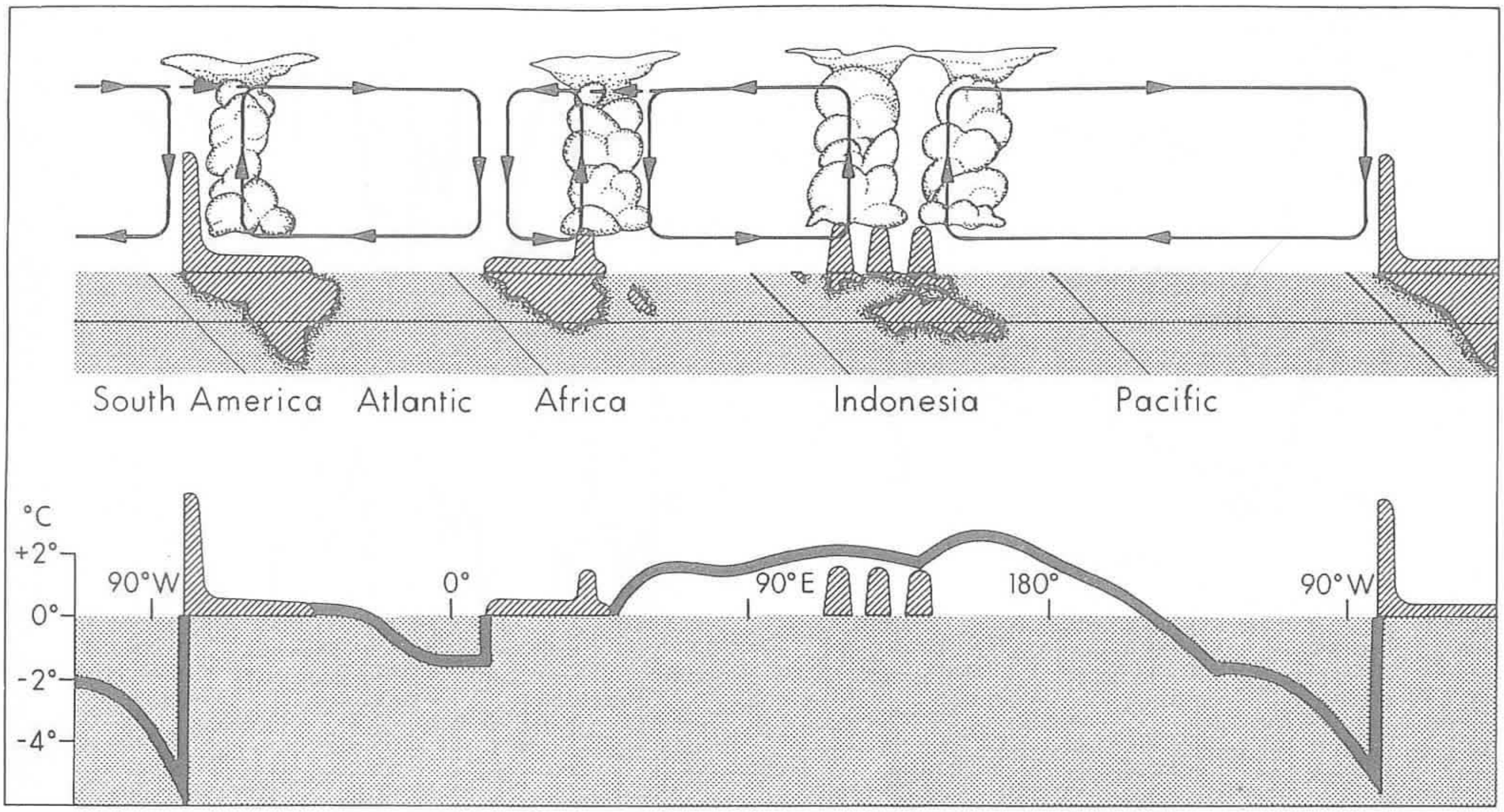

Figure 3. The Walker circulation along the equator, resulting in rising air and heavy rains over Indonesia, Africa and Brazil. Its strongest branch over the Pacific is related to the sea surface temperature; it is warm where air is rising and cool where air is sinking.

level (Figure 4), while temperatures in the eastern equatorial Pacific and especially off the coast of Peru are low. The temperature difference between the east and west enhances the atmospheric circulation and in particular the Walker cell. Thus ocean and atmosphere are in a stable high intensity state of positive feedback. This state can last for several years and develops very slowly.

During the low-intensity state, both the Easter Island High and the Indonesian Low are weak, and the pressure gradient between them is weak. Consequently the southeast trades are weak, equatorial upwelling is weak and the South Equatorial Current is slow. The eastern Pacific is warm. The temperature difference between east and west is small and as a result the Walker circulation is weak. This situation is typical for El Nino conditions. Whereas an actual El Nino event lasts only 14 to 16 months, bridging two southern summers, the low-intensity state may linger for several years. This occurred after the 1957/58 El Nino, and since the 1976 El Nino event the system has not yet changed from the low intensity to the high-intensity state.

Now an important question is: What terminates a stable state? Is it the ocean, or is it the atmosphere, or does ocean-atmosphere interaction trigger the switch from one state to the other?

El Nino

The termination of the high-intensity state results in El Nino. After the southeast trade winds have been abnormally strong for an extended period during a high-intensity state, they eventually will decrease. Such a decrease occurs annually during southern winter, but only when the decrease is particularly widespread and intense will a strong El Nino event be triggered. The collapse of the wind field causes an equatorial Kelvin wave to pass from the western to the eastern Pacific in about 60 days. The energy for the Kelvin wave is provided by the accumulated warm water in the western Pacific and the collapse of the winds only triggers it. When the Kelvin wave impinges on the coast of South America, downwelling occurs and warm waters accumulate off the coast (Figure 4). The south Equatorial Current decreases in strength, so cool advection in the Peru Current decreases. Equatorial upwelling decreases both because of the Kelvin wave and because of the weaker winds, and consequently equatorial waters warm rapidly.

Although the ocean response to the collapse of the wind field is well understood, the reason for the collapse of the wind field is essentially unknown. Is the high-intensity state simply "running out of steam;" or is the collapse of the wind field a random event? To what degree is ocean-atmosphere interaction involved?

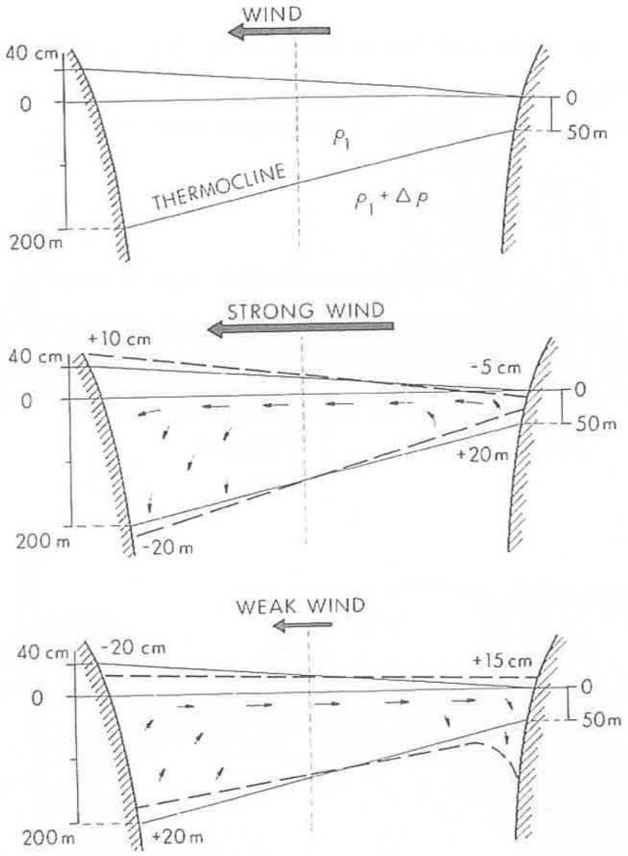

Figure 4. The response of the thermal structure of the equatorial Pacific to changing winds. Top: under normal conditions sea level rises to the west and the thermocline deepens. Center: this situation is amplified during strong trade winds. Bottom: when winds relax, water sloshes east, which leads to a deepening of the thermocline along South America and a rise in sea level. In the western Pacific, sea level drops and the thermocline rises.

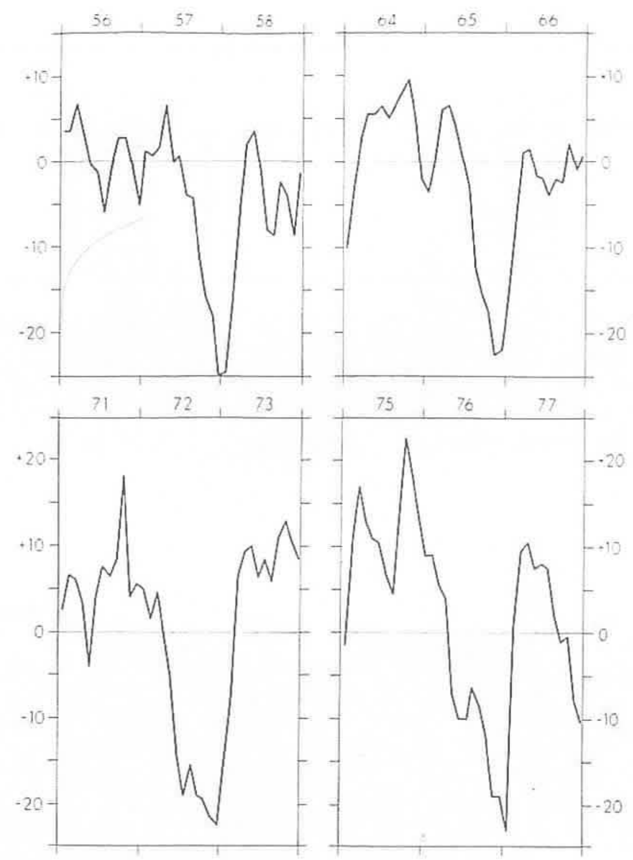

Figure 5. Sea level at Truk Island during the four most recent El Nino events, showing the year-long decline during El Nino and the rapid termination of each event.

These are the questions which will have to be answered in order to understand fully the Southern Oscillation. The warm sea surface temperatures off Peru are certainly not the trigger for El Nino, as was earlier suggested, because when they appear, El Nino is already in full swing and the Kelvin wave triggered by the collapse of the wind field in the western Pacific has arrived off Peru. The warmer waters off Peru and along the equator will, however, contribute to the maintenance of the low-intensity state once it is established. The sea surface temperatures can not cause the collapse of the wind field.

The Termination of the Low-Intensity State

The termination of El Nino and the end of the low-intensity state are two different matters. The termination of El Nino is extremely rapid, but the low-intensity state may linger on for several years. During the course of El Nino, water drains from the western Pacific over a period of more than a year, sea level drops, and the thermocline slowly rises (Figure 5). This loss of warm water is suddenly stopped and sea level increases to normal values within about two months as soon as the trade winds increase again. It is not clear at this time why the response is that rapid nor from where the water causing the rise in sea level comes. Almost certainly one can exclude a source from the east, because westward-traveling Rossby waves are three times slower than the eastward traveling Kelvin waves. More likely is a movement of water from both hemispheres toward the equator, but the associated flows have not yet been determined.

The Role of Ocean-Atmosphere Interaction

It appears that ocean-atmosphere interaction is strongly involved in maintaining the stable states. During the high-intensity state, when the waters along the equator are cool, the flux of heat from the ocean to the atmosphere is small, like in 1973 (Figure 6). Because of the low equatorial temperatures the evaporation remains small in spite of the stronger winds. In contrast, during the warm years, like in 1972 during El Nino, the flux of heat from the ocean to the atmosphere is large. The higher sea surface temperatures in warm years during the low-intensity state have more effect on the heat flux than do the lower wind speeds. Consequently more latent heat and more moisture is supplied to the atmosphere in warm years than in cold years, in full agreement with the earlier views of Bjerknes. Thus in warm years rain must

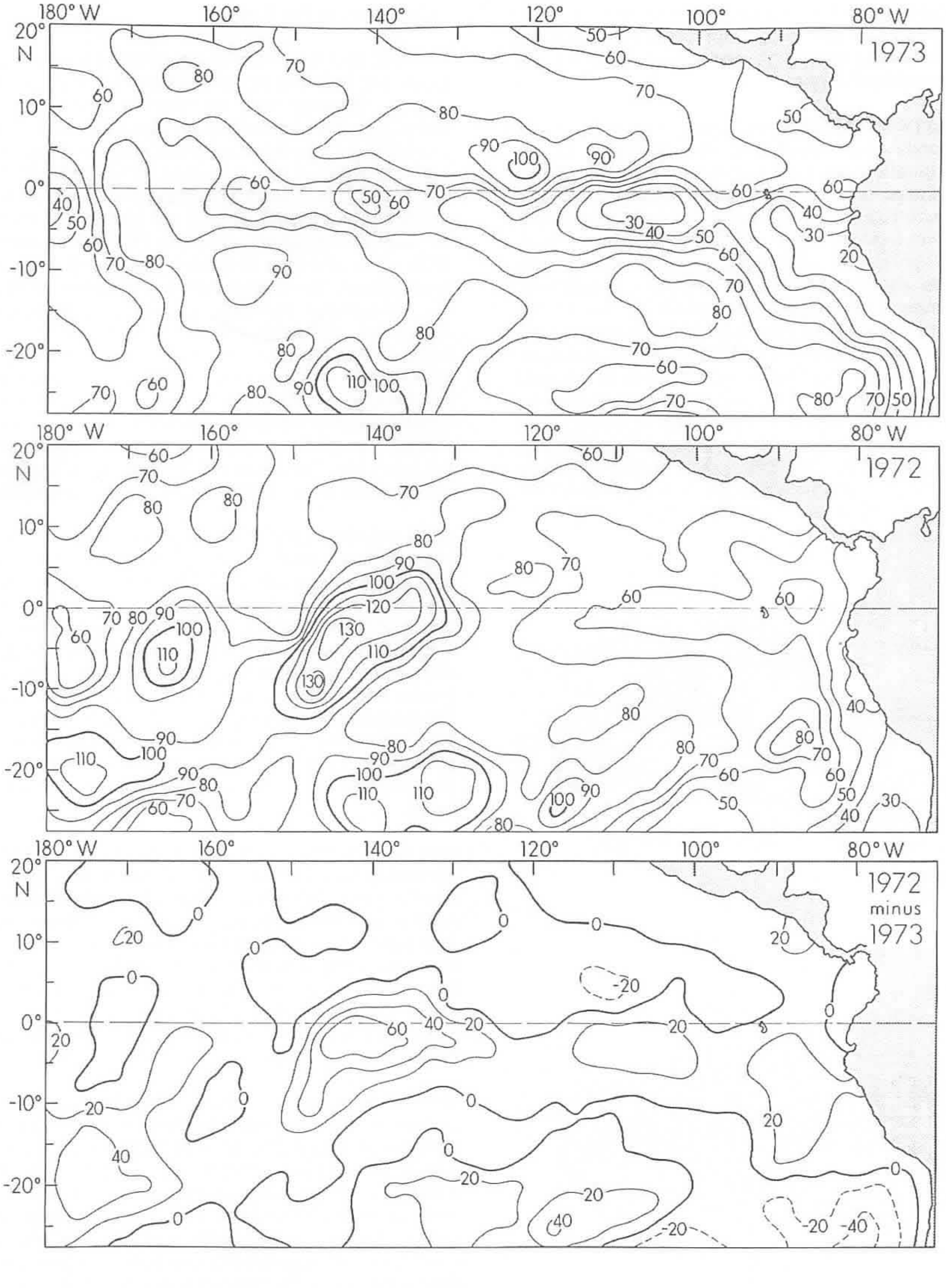

Figure 6. Transfer of evaporative and sensible heat from the ocean to the atmopshere in Wm^{-2}. Top: during a high-intensity state in June, July and August 1973. Center: during an El Nino event in June, July and August of 1972. Bottom: The difference (1972 minus 1973).

start earlier along an air trajectory than in cold years. This relation between the circulation and the moisture transport is apparent in both the annual signal and the interannual fluctuations.

Charts compiled by Albrecht (Figure 7) show the transfer of moisture from areas of net evaporation to areas of net precipitation over the Indo-Pacific region. In August the southeast trade winds reach far into the western Pacific and rain falls chiefly over the northern hemisphere, over Indochina and the Philippines. In contrast, during February the trajectories of the southeast trade winds are shorter and an intensive convergence with heavy rains stretches from Indonesia to Tahiti. The same general pattern is developed during the two stable states of the Southern Oscillation. During the high-intensity state air trajectories reach further to the west and the rainfall area lies over Southeast Asia, but during the low-intensity state the rainfall area is shifted east and lies over the western Pacific between the date line, New Guinea and the Philippines. This shift in the main rainfall area is of course indicative of an eastward shift of the entire Walker circulation system.

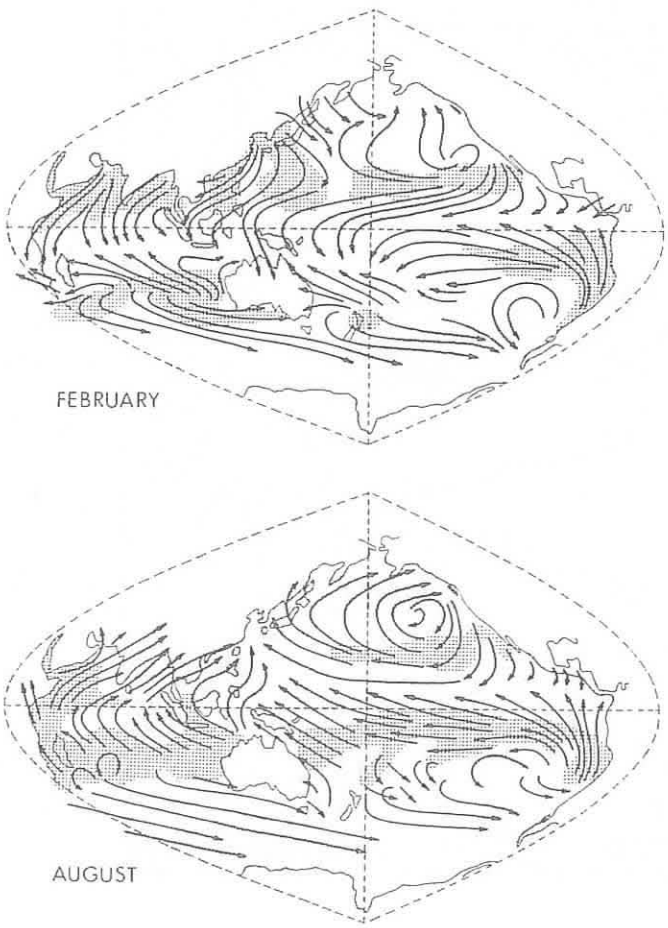

Figure 7. Charts of moisture transfer between areas of net evaporation (dotted) and areas of net precipitation (shaded) in August (top) and February (bottom) (after Albrecht).

The Cycling of the System

The high- and low-intensity states of the Southern Oscillation are only the extreme situations of a vacillating system. Bjerknes was the first to hypothesize how ocean and atmosphere interact to produce such a cycle, and his ideas have been put into a schematic diagram by Warnecke (Figure 8). Let us start with the high intensity state, when trade winds are strong, the Peru Current and the South Equatorial Current are strong and cold and the Walker circulation is intense. This is the case when little or no rain falls at Kanton Island and when no El Nino occurs. The strong Walker circulation dominates the atmospheric situation, resulting in a weak Hadley circulation. The Hadley cells feed moist air from both hemispheres toward the intertropical convergence zone, where air rises, and the moisture is released as rain. At higher levels the air returns poleward to the subtropics, where it sinks and completes the cycle. A weak Hadley circulation also implies a weak vorticity transport from the tropics to the subtropics and causes a weakening of the subtropical high-pressure system.

Once the subtropical highs, especially the Easter Island High, become weak, the trade winds relax and an El Nino event will be triggered. This results in a warm Peru Current, a warm equatorial Current, and a weakening of the Walker circulation. The weak Walker circulation allows rain to fall earlier along the air trajectory; consequently the rainfall area shifts east into the western Pacific and excessive rainfalls are observed at Kanton. The weak Walker circulation together with warmer equatorial waters leads to a stronger Hadley circulation and a stronger vorticity transport to the subtropics, which in turn intensifies the subtropical high and closes the cycle.

I am using the diagram (Figure 8) only as an example for a possible scenario, as many aspects of this cycle still need to be explored and confirmed and phase relations need to be established from often scanty observations. One important aspect of this scenario is the lack of a mechanism that determines the period of the cycle, and this may not be accidental. I believe that such a mechanism may not even exist, and therefore the cycle may be as fast as three years and as long as a decade, as has been observed.

The low-frequency behavior of the ocean-atmosphere system is well illustrated by time series of relevant parameters during the period 1949 through 1978, which includes the El Nino events of 1957, 1965, 1972 and 1976 (Figure 9). The westward component of the wind stress over the central equatorial Pacific shows large interannual variations during which wind stress increases by a factor of two between the low- and the high-intensity states. The sea level difference between Truk Island in the western Pacific and Talara in Peru follows the wind pattern. This difference is large when winds are strong and small when winds are weak, during El Nino. The time series for the Southern Oscillation index given by the difference of atmospheric pressure between Easter

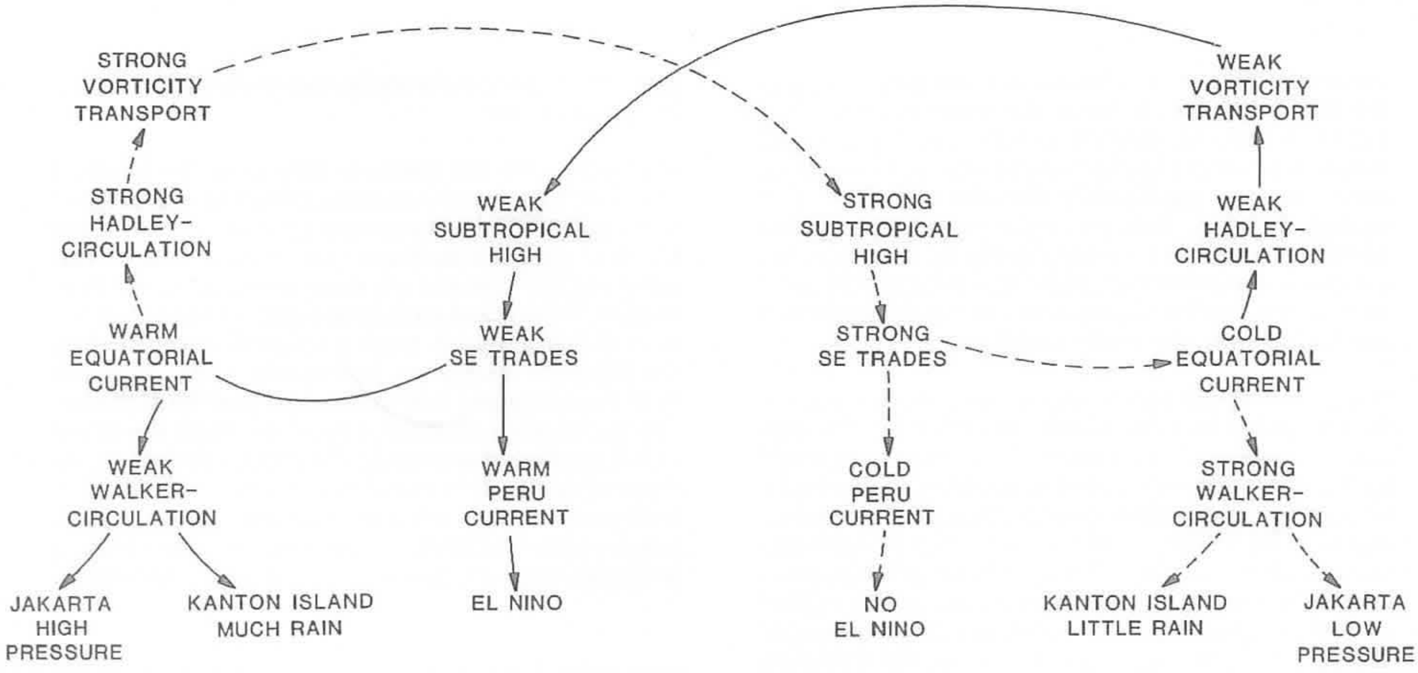

Figure 8. A schematic diagram of Bjerknes' scenario of events during a Southern Oscillation cycle according to Warnecke.

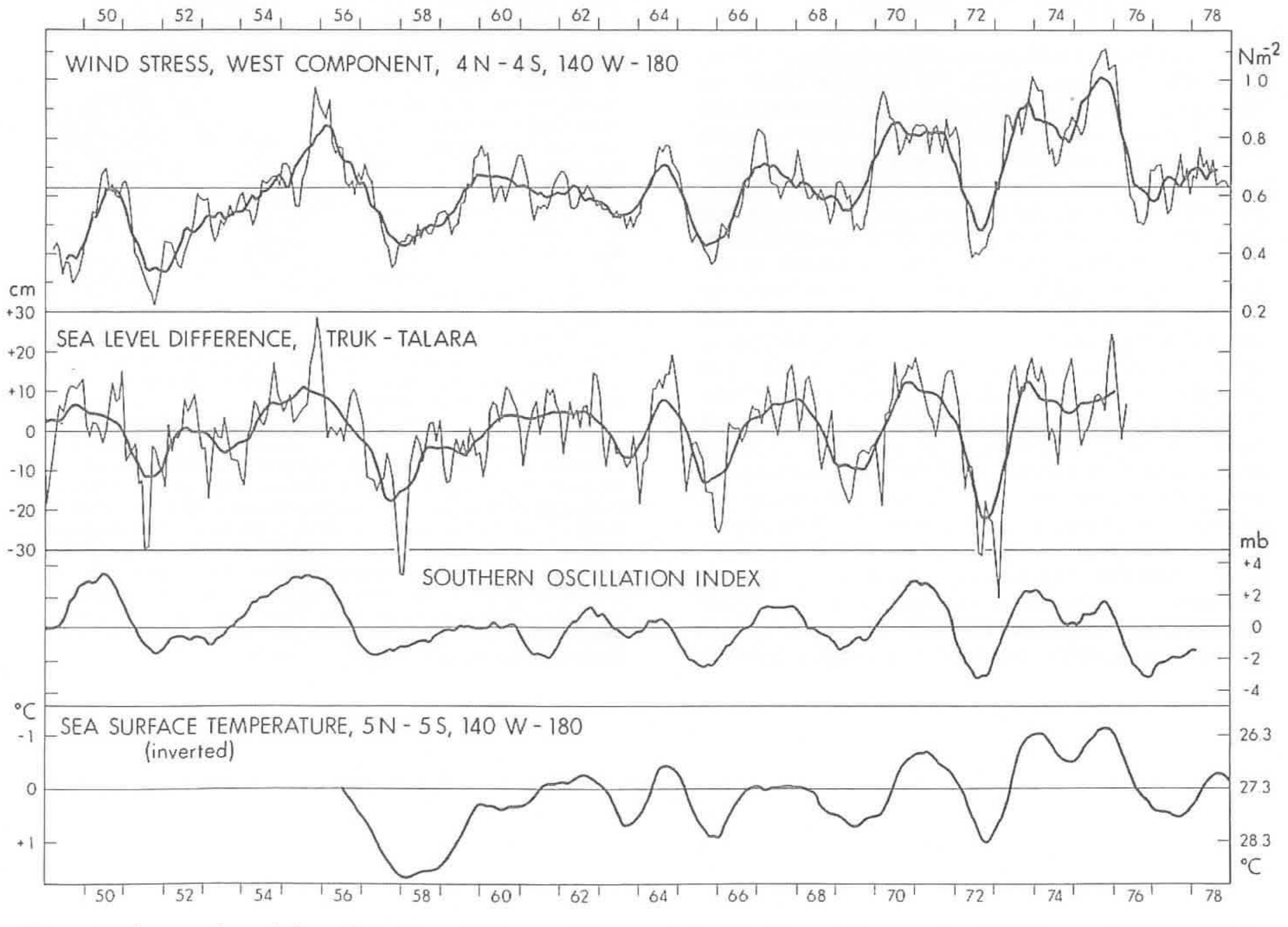

Figure 9. Time series of the wind stress in the central equatorial Pacific, of the sea level difference between Truk Island and Talara, Peru, of the Southern Oscillation and of sea surface temperature in the central Pacific from 1949 through 1978. The heavy curves are 12-month running means, the thin curve gives 5-month running means for the wind stress and monthly means the sea level difference.

Island and Jakarta, and the sea surface temperature in the equatorial Pacific show the same low-frequency signal. A spectral analysis reveals that for a period longer than two years, phase differences between these curves are not significantly different from zero. This analysis indicates that the ocean atmosphere system fluctuates essentially synchronously. As the ocean has a much larger inertia to changes than the atmosphere, it also means that the atmosphere can rapidly adjust and respond to any given ocean situation.

The preceding discussion and analysis lends credence to the opinion that the switch between high- and low-intensity states of the system might not be governed by its internal dynamics, but instead might be caused by turbulent bursts, namely sudden unexpected developments in the system, which trigger a change from one stable state to the other. This hypothesis is in full agreement with the concept of the ocean-atmosphere system as a fluid dynamic system ruled by random turbulent events. In fact, the search for a deterministic mechanism for the Southern Oscillation might be futile.

CONCLUDING REMARKS

The low-frequency vacillations of the ocean-atmosphere system that are apparent in the Southern Oscillation seem to indicate that the Southern Oscillation is actually the link between the predominantly annual variations in the northern hemisphere and the predominately interannual variations in the southern hemisphere. Ocean-atmosphere interactions seems to play a significant role in the process, and I will outline some thoughts in this direction. The Indonesian low-pressure system is subject to a rather regular annual migration between the two hemispheres, but the location and extent of it vary somewhat from year to year. If the Indonesian Low extends through random variations of its location more toward the warm western Pacific Ocean than over the Indonesian waters, it probably gets into a feedback mode. Rainfall extends further east, air trajectories become shorter, and El Nino develops. If feedback is sufficiently strong, the ocean-atmosphere system will develop into a low-intensity state. Thus the interaction of the regular annual variation of the atmosphere in the northern hemisphere with the interannual variations of the southern hemisphere may produce vacillations in the tropical regions of the Indo-Pacific region. These vacillations will be of unspecified period, but the switch between high- and low-intensity states will be strongly linked to the annual signal.

We began with the question: Why does the Southern Oscillation oscillate? A definite answer can not be given at the present time. The more appropriate question may be: How does the Southern Oscillation oscillate? This latter question can and will be answered by more observations of the ocean-atmosphere system and of the processes that govern it. Such a research effort to study the Southern Oscillation is presently being organized both nationally and internationally. From the forthcoming observations we should learn more about the nature of the oscillation and about the phase relations in the chain of events. This research may eventually lead to a prediction of the ocean-atmosphere system during stable states. The prediction of turbulent events leading to sudden changes, however, is very likely impossible.

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Dr. Wyrtki was born in Tarnowitz, Germany in 1925. He received his education at the University of Marburg, Germany, and at the University of Kiel, Germany, receiving his Doctor of Natural Sciences in 1950, *magna cum laude,* from the latter.

Professor Wyrtki has been a member of the steering committee of the North Pacific Experiment (NORPAX) since 1972 and is chairman of the executive committee. He is on the editorial board of the *Journal of Physical Oceanography* and the advisory board of the National Oceanographic Data Center. He is also a member of the SCOR Working Group on the Prediction of El Nino. He is the editor of the *Atlas on Physical Oceanography of the International Indian Ocean Expedition* and the author of over 100 papers published both here and abroad. He is a member of many professional societies, including the American Geophysical Union, American Association for the Advancement of Science, American Geographical Society, American Meterological Society and the Hawaiian Academy of Science.